Determining the Depths of Magma Chambers beneath Hawaiian Volcanoes using Petrological Methods

Senior Thesis

Submitted in partial fulfillment of the requirements for the

Bachelor of Science Degree

At The Ohio State University

By

Andrew Thompson

The Ohio State University

2014

Approved by

MBarton

Michael Barton, Advisor
School of Earth Sciences

Table of Contents

Abstract

Determination of the depths of magma chambers of Hawaiian volcanoes has been a major topic of interest for geologists and volcanologists in the past since the development of the plate tectonics theory in the 1950s. This is because scientists have wondered how Hawaii's volcanoes fit into the plate tectonic theory since Hawaii is located in the middle of the massive Pacific plate, far from any plate boundary. All of these scientists have been trying to understand how the plumbing systems of these volcanoes work above the hotspot that accounts for Hawaii's volcanism in the crust of the Pacific plate.

Recent measurements of the composition of the magmas used in this research have led to the observation that each volcano on the big island of Hawaii has a slightly different composition, supporting the hotspot theory of volcanism in terms of types of magmas that are coming from the hotspot below as the Pacific plate moves across the hotspot. Petrologists, volcanologists, geochemists, and geophysicists have been working to get an understanding of how moving over the hotspot affects the volcano's magma composition over time.

Petrological methods to determine the pressure of partial crystallization of Hawaiian magmas allow identification of the magma chambers depths, and suggest how the plumbing systems work in these volcanoes and where those plumbing systems will be located, in terms of depth.

Acknowledgements

First and foremost, I would like to thank my parents for all their support over the years on everything that I've wanted to do. I wouldn't be in the place I am now without their support and advice, for which I'm extremely grateful. I'd like to thank my brothers, aunts, uncles, cousins, and other extended family who have also voiced their support throughout the years.

I am so thankful for the help provided and I deeply appreciate the advice and support by the Faculty and Staff of the School of Earth Sciences at The Ohio State University. I am forever grateful for the countless hours spent lecturing on topics and the time they put in to teaching these courses. I would like to thank Dr. Michael Barton, specifically, for being the person that really opened my mind to petrology and why certain processes work the way they do. And I would also like to thank Dr. Anne Carey and Dr. Karen Royce for putting up with all of my ridiculous questions and dealing with me over the past few years.

Lastly, I'd like to thank my roommates and friends for all the fun times we've had, both here in Columbus and on various school trips and classes. You all deserve personal shout-outs, but you know who you are. I am deeply appreciative of all the help, advice, and support you have all given me. Thank you.

Introduction

The overall goal of this research is to determine the depth of magma chambers beneath Hawaiian volcanoes using petrological methods. I will be focusing on the Hawaiian volcanoes of Kilauea, Loihi, Mauna Kea, and Mauna Loa, all located on the big island of Hawaii. I will be using compositional data for magmas, represented by glasses, from the four volcanoes and a petrological method to calculate the pressures of partial crystallization of these magmas. These results will be used to determine the depth of these magmas. The results will provide insight into the nature of the plumbing systems beneath these volcanoes, will shed light on how these volcanoes work, and will allow consideration of the relationship between volcanism and the hotspot under the Pacific plate. In addition, the results obtained from each volcano will be compared to establish possible differences between them; having in mind that they're all on the same island and not too far away from one another.

A further understanding on how intra-crustal processes work will allow scientists to gain a better understanding of these volcanoes on the Hawaiian Islands and especially how their plumbing systems extend beneath the surface. Further study through geophysical methods will provide a clearer picture in terms of the plumbing systems beneath the surface, but the Petrological method used in this research will allow a better understanding of the relationship between depth and compositions of these Hawaiian magmas.

This research builds on the work of Ditkof (2010). She determined the pressures of partial crystallization of magmas from Hawaii using the same method as used in this work. However, the number of samples used in the present research is considerably larger than that used by Ditkof. The results obtained herein should, therefore, provide more reliable estimates of the pressures of partial crystallization of Hawaiian magmas.

Geologic Setting

Hawaii is an archipelago of eight major islands and several smaller atolls, islets, and underwater seamounts. The islands were formed as the Pacific plate moved relatively quickly in a northwestern direction over a hotspot in the Earth's mantle. Slowly, over several millions of years, volcanism from the hotspot propagated through the Pacific plate and formed each island in the Hawaiian chain, one at a time. The process has continued and the latest island formed is Hawai'i, which formed approximately 0.4 million years ago (Ma) and continues to be volcanically active over the hotspot today.

For this research, the only island of interest is the big island of Hawai'i, which is the youngest and largest island of the Hawaiian Island chain. This is the only island with active or recently active volcanoes. Hawai'i encompasses five major shield volcanoes, two submerged volcanoes, and two active ridge zones (Sherrod et. al, 2007). The five major shield volcanoes are Hualalai, Kilauea, Kohala, Mauna Kea, and Mauna Loa. The two submerged ones are Loihi and Mahukona, which is not active. The two active ridge zones are the Hilo Ridge and the Puna Ridge, which extend from Kilauea and Mauna Kea off the island on a northeast-southwest trend (Sherrod et. al, 2007). The volcanoes of concern for this research are Kilauea, Loihi, Mauna Kea, and Mauna Loa.

Mauna Kea is the highest point on the island of Hawai'i and the only volcano to be glaciated on the Hawaiian Islands and the most symmetrical of the numerous volcanoes, while lacking well-defined rift zones (Sherrod et. al, 2007). The volcano is located on the north-northeastern part of the island, with lava flows that formed over a long period of time, over tens of thousands of years.

Mauna Kea's oldest stratum is assigned to the Hamakua volcanics, which are found on all flanks of the island. These volcanics are divided into two members, the lower assigned to shield-stage volcanism and the upper assigned to post-shield stage volcanism (Sherrod et. al, 2007). The difference between these two members is described as gradational (Sherrod et. al, 2007) and seems to indicate continuous deposition of those volcanic sediments during Mauna Kea's formation and subsequent eruptions since that time, which dates to between 300 thousand years (Ka) and 64–74 Ka. The youngest stratum is the Laupahoehoe volcanics, which serves as a transition zone between tholeiitic shield and alkaline (post-shield) magmas, dated to around 4.5 Ka (Sherrod et. al, 2007).

Mauna Loa covers most of the island of Hawai'i, but mostly forms the central part of the island while extending to the northwestern coast of the island. Shield stage volcanic flows, with tholeiitic lavas, are found offshore near the volcano's northwest rift zone (Sherrod et. al, 2007). These flows were dated to about 130 Ka, roughly in the same time frame as Mauna Kea.

Kilauea, which has been continuously erupting since 1983, is located on the east-southeast portion of the island of Hawai'i. It is the youngest emergent volcano on the island and is perhaps the most active volcano in the world (Sherrod et. al, 2007). Kilauea's oldest stratum included pre-shield stage alkaline basalt lavas dated to 375 Ka, which is consistent with the cycle of hotspot volcanics. Boreholes and other drillings indicate that the entire exposed tholeiitic shield stage volcanics are younger than 225 Ka (Sherrod et. al, 2007). Most of the lava flows on Kilauea's slopes are lava flows formed less than 1,500 years ago, indicating a recent and active volcanic history, which is consistent with current activity around the volcano.

Loihi is one of the youngest volcanoes in the Hawaiian Island chain and is still located beneath the surface of the ocean to the south-southeast of the island of Hawai'i. It remains approximately 978 meters below the surface and is believed to consist mostly of alkaline magmas (Sherrod et. al, 2007). This volcano has the least known about it since it still lies below the surface of the ocean. Future studies will reveal more about the volcano, in addition to the other numerous volcanoes on the island of Hawai'i.

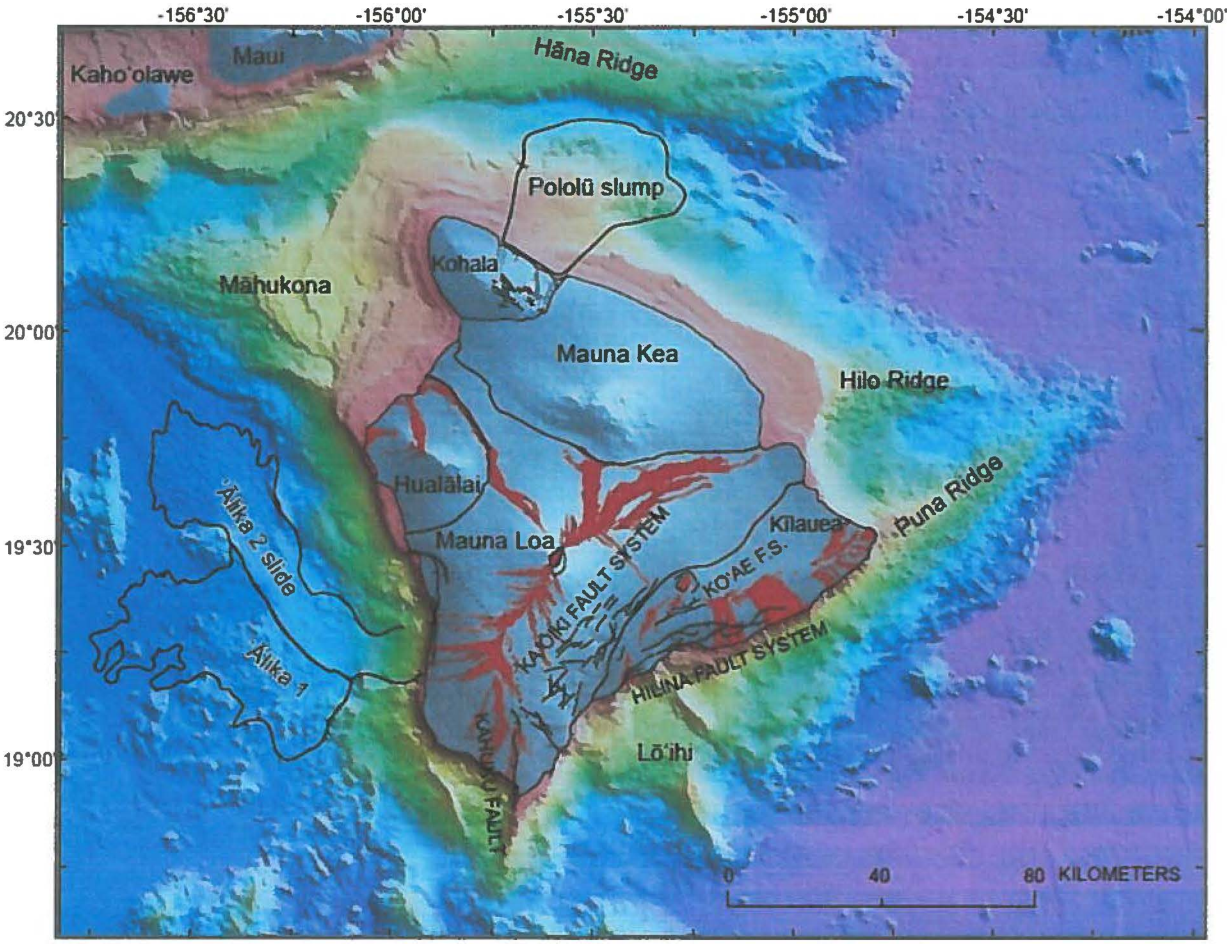


Figure 1: Map of volcanoes on the island of Hawai'i (Sherrod et. al, 2007)

Methods

The depths of magma chambers can be determined from the calculated pressures, because there is a simple relationship between calculated pressure and depth. The pressure of crystallization calculations can be determined by the location of liquid compositions on the Olivine-Plagioclase-Clinopyroxene cotectic (Kelley & Barton, 2008). This petrological method uses the analyses of volcanic glasses (representing quenched liquids) to help determine the pressure of crystallization, and ultimately the depth.

This pressure of crystallization represents the pressure prior to eruption of these magmas. The chemical composition of the liquid, containing the minerals olivine, plagioclase, and clinopyroxene, changes systemically with changes in pressure (Kelley & Barton, 2008). The volcanic glasses analyses indicate chemical equilibrium between olivine, plagioclase, clinopyroxene, and liquid at a particular depth of where the magmas spent time prior to the ascent of magmas preceding an eruption. This particular depth is represented by a pressure value.

Yang et al. (1996) presented three equations that describe the compositions of liquids lying along Olivine-Plagioclase-Clinopyroxene cotectics. The equations include compositional parameters as well as terms for temperature and pressure. The volcanic glasses analysis determines the compositions of the liquids, which can then be used to predict the pressures (and temperatures) of the glasses at the equilibrium composition (Kelly & Barton, 2008).

Filtering

The petrological method required to complete this research must use samples that are determined to be reliable and accurate. The process of filtering potentially unreliable or inaccurate analyses of samples from the data set used for this research allows this petrological method to determine results that minimize potential error. The filtering used for this research has four steps: three of which are based on chemistry and one which is based on uncertainty.

The first step of filtering is to remove any samples that have anomalous compositions that fall off dense data arrays on variation diagrams. Such arrays are determined from graphs of major oxides versus MgO concentration. The second step of filtering is to remove samples that have a greater than 52% SiO_2. This removes compositions that are not basalts and is justified because the methods used to determine pressure is calibrated only for basaltic compositions. Any sample with less than 52% is considered appropriate for this research.

The third step of filtering is to remove any samples that have a greater than or equal to 7% MgO concentration. Samples with more than 7% MgO do not lie on the Olivine-Plagioclase-Clinopyroxene cotectic and cannot therefore be used in this petrological method. The fourth and final step of filtering is to remove any samples that have a greater than 1.26 value for pressure uncertainties (1σ).

Volcano Name	Total Number of Samples	After Chemical	After Uncertainty
Kilauea	762	463	463
Loihi	118	65	54
Mauna Kea	549	360	360
Mauna Loa	287	69	69

Table 1: Filtering from total samples from each volcano to number of samples after chemical filtering and number of samples after uncertainty filtering

This data base is composed of published and unpublished analyses. The total number of analyses combined is 1,716 analyses. This data base was compiled by Michael Barton.

CIPW Normalization

CIPW Normalization calculations are a normative mineralogy calculation based on the geochemical make-up of the rock in order to calculate idealized mineralogy. These values are calculated from the initial magmatic compositional values, after chemical and uncertainty filtering has been completed. This normalization method forms the basis to determine the minerals present in these magmas.

The CIPW Norm calculates the amounts of certain minerals present in the magmas such as Quartz, Olivine, Diopside, Hypersthene, Orthoclase, Albite, Anorthite, Magnetite, Ilmenite, and Apatite. In addition, the CIPW norm calculates values for Solidification Index, Differentiation Index, Color Index, and Agpaitic Index. This normalization gives a very good representation of what minerals are present in certain magmas that are measured and calculated from the initial compositional values of those magmas. In addition, this normalization provides an easy way for some of these magmas to be classified based on the mineralogical composition of the magmas.

In Kilauea, the CIPW Norm shows a large quantity of quartz, hypersthene, and a few values that show that olivine is present in smaller quantities, while the Kilauea magmas lack a large amount of alkaline magmas. This indicates that Kilauea is mostly tholeiitic. In Mauna Kea, the CIPW Norm shows a large quantity of quartz, hypersthene, and some olivine like Kilauea, however, Mauna Kea has less quartz and more values indicating the presence of olivine than Kilauea. These small differences in composition do not change the overall classification that Mauna Kea is also tholeiitic.

In Mauna Loa, the CIPW Norm shows a large quantity of quartz, hypersthene, as well as similar levels of alkaline magmas to Kilauea and Mauna Kea, but Mauna Loa doesn't have any olivine values among the samples. This is the main difference between Mauna Loa, Mauna Kea, and Kilauea. Mauna Loa is also classified as tholeiitic. In Loihi, the CIPW Norm shows a much different picture than with the other three volcanoes included in this research. Loihi has an abundance of alkaline magmas, unlike Kilauea, Mauna Kea, and Mauna Loa. Loihi also lacks large quantities of quartz and hypersthene, while containing large quantities of olivine and nepheline. Loihi is classified as alkaline.

Classification

The classifications of the magmas from each volcano are mostly dependent on how the CIPW Normalization calculations work and what minerals are present in the compositions of these magmas. Additional information is provided by the analyzed compositions of the magmas from each volcano which can be used to calculate weight percent of SiO_2 versus weight percent of Na_2O and K_2O, added together. The graphs for the silica to alkaline ratio of each volcano can be seen in the results section under each respective volcano.

For Kilauea, Mauna Kea, and Mauna Loa, all of the results fall into the sub-alkaline Basalt category, which has lower total alkalis content than magmas that can be considered Trachybasalts, like some of those from Loihi. Loihi has magma compositions that fit into both the Basalt and Trachybasalt categories. The silica compositions of these magmas range from 48 to 52%, while alkaline compositions range from 2 to 6%.

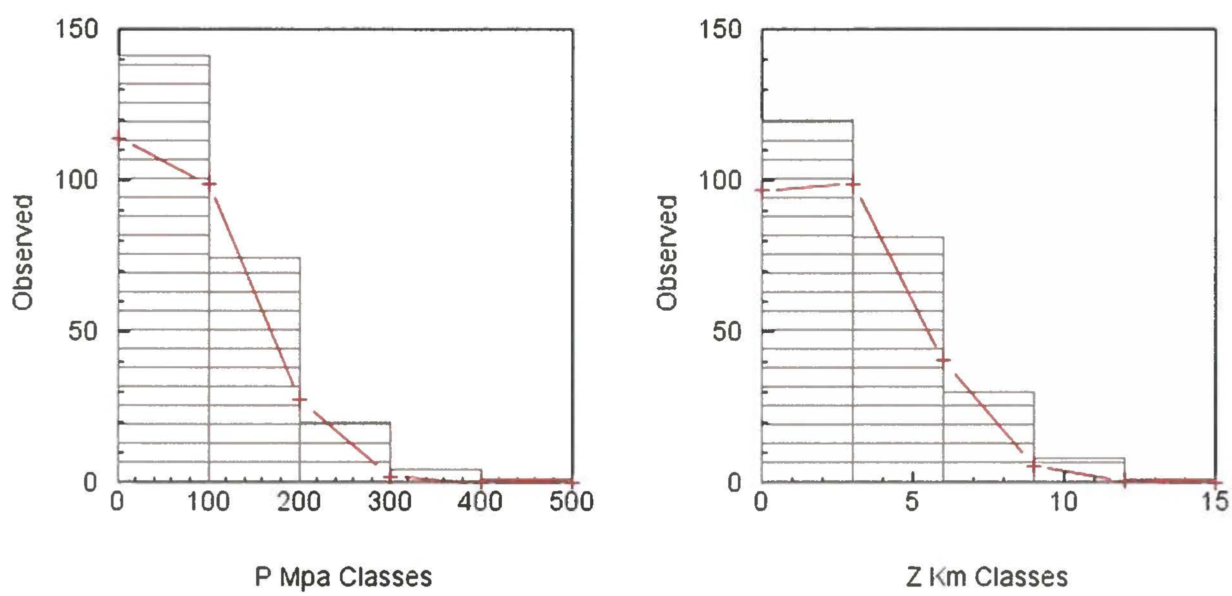
Loihi has higher alkaline content and lower silica content than the other three volcanoes. Mauna Loa has higher silica content and lower alkaline content than the other three volcanoes. Kilauea and Mauna Kea both have alkaline and silica content that are between the values for Loihi and Mauna Loa. These middle values average about 51% silica content and 3% alkaline content. Other classifications can be determined by the range of compositions for MgO, Al_2O_3, FeOT, and CaO. Kilauea, Mauna Kea, and Mauna Loa have values of MgO that are close to or around 7%, while Loihi has lower MgO content, on average. For FeOT, which is around 11% for Kilauea, Mauna Kea, and Mauna Kea, Loihi is slightly higher at 12% FeOT content. For Al_2O_3, all volcanoes have similar average values around 13% content, and for CaO, all volcanoes have similar average around 11% content.

Results

In this research, the same method was used to determine the pressure of crystallization beneath four different volcanoes: Kilauea, Mauna Kea, Mauna Loa, and Loihi. Each volcano is slightly different, so the results for each will be described separately in order to provide a clear explanation for what processes affect each individual volcano and what the depth measurements for each volcano's magma chambers are like.

Kilauea

Kilauea has the distinction of being one of Hawaii's most active volcanoes in the past 30 years, with a continuous eruption ongoing since 1983. It also benefits from being one of the most intensively studied volcanoes in the world. This allows for a lot of information to be available for how the volcano is structured, how it behaves, and generally where its magma has originated.



Figures 2 & 3: The grey histogram blocks represent pressure or depth classes versus observed values, while the red line represents pressure or depth classes versus expected values.

After calculation of the pressure and depth of each individual glass sample in the data set for Kilauea, the average depth and pressures were determined by averaging the values. Then the distribution of the depth and pressures of these magma chambers were determined by plotting, in a histogram, the pressure classes, in megapascals, versus observed and expected measurements, and plotting the depth classes, in kilometers, versus observed and expected measurements. These plots provide a visual representation of how the magma chambers are generally structured and ordered beneath the volcano (Figures 2 & 3).

The histograms in Figures 2 & 3 illustrate that the majority of the magmas in the data set for Kilauea originated in magma chambers that were at less than 10 km depth, with most at less than 5 km depth. This just gives a pressure and depth for these magmas, but does not illustrate the specific plumbing below the volcano. The depth of these magmas agrees with the measurements using geophysical methods. The values of the shallow and deep rift zones in Kilauea along the East Rift Zone were measured to be 4 to 10 km of depth below the surface (Ryan, 1988). Petrological methods showed similar values of 4 to 6 km of depth (Helz & Wright, 1996).

The East Rift Zone of Kilauea, slightly east-southeast of the volcano, is a very important area of study by both petrological and geophysical methods. In addition to the calculated depths agreeing with the geophysical data, the pressures also agree, measuring between 0 and 275 MPa (Ryan, 1988). With both depth and pressure measurements agreeing between Petrological and Geophysical methods, these measurements should be considered valid and accurate for Kilauea.

Additional geophysical measurements indicate a link between the East Rift Zone and the Southwest Rift Zone by linear gravity highs (Kauahikaua, 2000). Along with information indicating depth and increased gravity, a better understanding of the plumbing and how the magma interacts with other, newer magmas can indicate how the plumbing of Kilauea works. For Kilauea, the initial compositional measurements can be used to determine the classification of the magmas. Composition of the Kilauea magmas plotted by the weight percent of SiO_2 versus the weight percent of $Na_2O + K_2O$ show that, by the classification scheme for igneous rocks, these magmas are sub-alkaline, tholeiitic basalts (Figure 4).

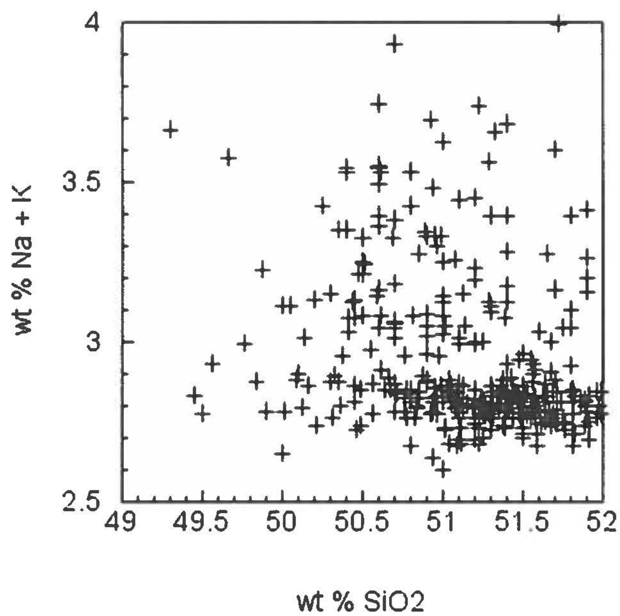
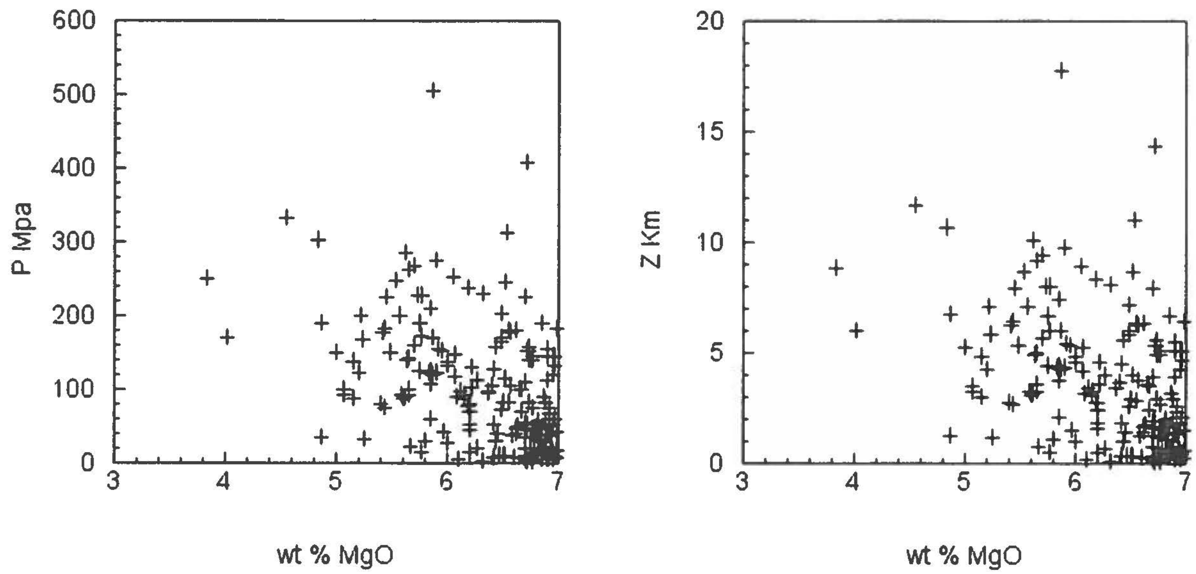


Figure 4: Showing silica versus alkaline ratio for Kilauea magmas.

The petrological methods used to determine pressure and depth provided a general idea of the plumbing beneath the Hawaiian volcanoes. Kilauea's plumbing system is characterized by existing magma mixing with new magma that is introduced into the same chambers (Helz & Wright, 1992). This conclusion agrees with the CIPW Normalization of Kilauea's magmas due to the different minerals that are included in the magmas, that otherwise would have reacted at different conditions and with different minerals.

Kilauea is a part of the Kea trend, in terms of Hawaiian volcanics (Dixon & Clague, 2001). This trend includes Kilauea and Mauna Kea, but is also tracked off to the northwest through the other Hawaiian Islands. These volcanoes share similar progressions of magma compositions. Kilauea will eventually develop compositions similar to that of Mauna Kea.

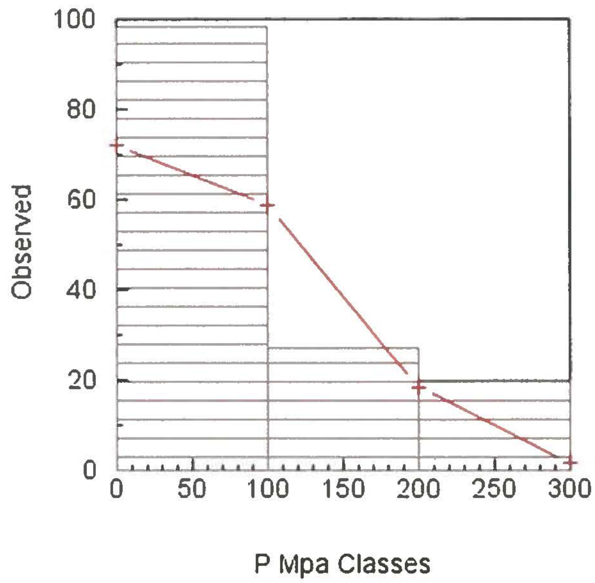
Plots of MgO concentration versus pressure and depth show a trend that has a negative slope indicating that the concentration of MgO increased as pressure and depth decreased (Figures 5 & 6). This observation is not consistent with magma evolution during crystallization at constant or decreasing depth (i.e. during magma ascent) and may indicate that magma mixing and/or assimilation accompanied crystallization.

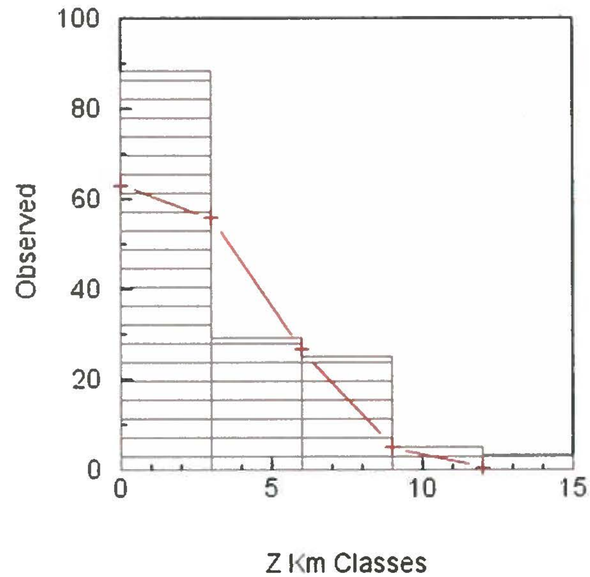


Figures 5 & 6: MgO concentration versus both P MPa and Z Km for Kilauea.

Mauna Kea

Mauna Kea is one of the largest volcanoes on the island and shares the Kea trend with Kilauea, having similar volcanic compositions (Dixon & Clague, 2001). The depth of the magma chambers at Mauna Kea are about what might be expected from the results obtained for Kilauea, assuming that Mauna Kea and Kilauea have similar plumbing systems.





Figures 7 & 8: The grey histogram blocks represent pressure or depth classes versus observed values, while the red line represents pressure or depth classes versus expected values.

Histograms show the distribution of magmas beneath the volcano of Mauna Kea (Figures 7 & 8). The vast majority of the magmas seem to originate from depths less than 3 km, with few measurements showing a depth of greater than 10 km. These results, in terms of depths of magma chambers, are about what was expected with the Kea trend. These results agree with results for samples that were dredged from 1.6 to 3.3 km of depth from the submerged flanks of the volcano, where the compositions were very similar to the Kea trend (Yang et al., 1994). An additional study indicated magma chamber depths between 2 and 7 km (Yang et al., 1999). The agreement between these studies and the data in this research indicates a strong support for the values calculated in this work from the pressures calculated for these samples. These compositions are close enough to illustrate that these results are reliable, as well as illustrating the Kea trend.

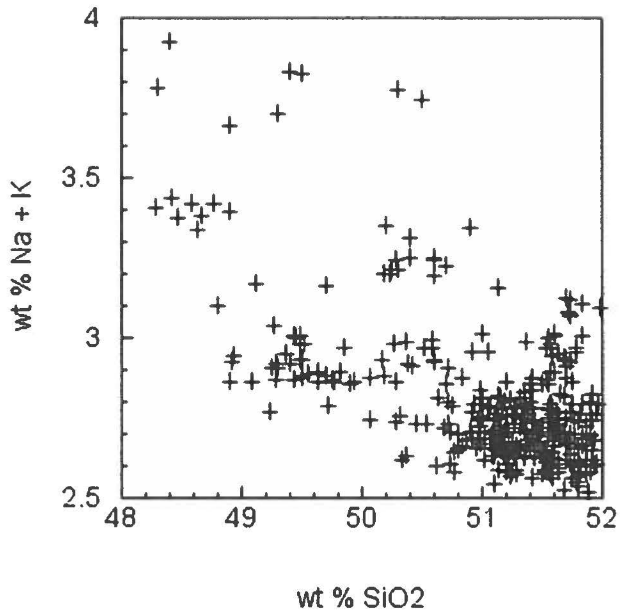
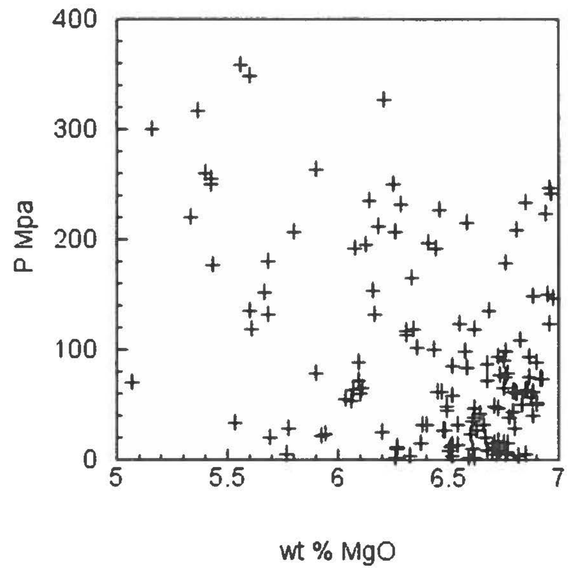
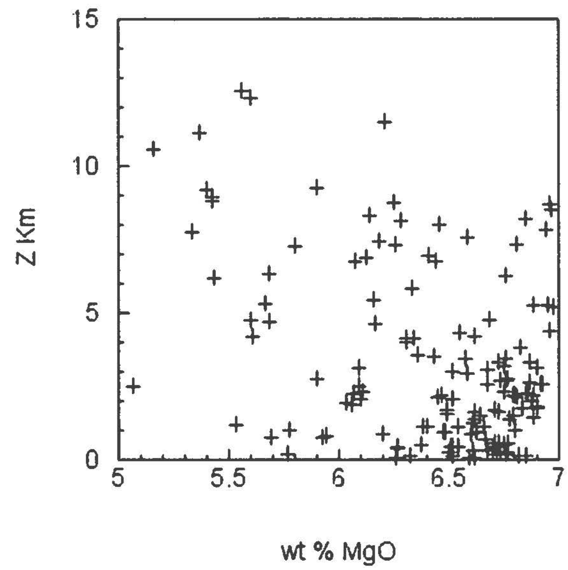


Figure 9: Showing silica versus alkaline ratio for Mauna Kea magmas.

Figure 9 shows the ratio between silica and alkaline content of the magmas from the Mauna Kea volcano. These values have higher silica, but still maintain the lower alkaline values that are characteristic of the Kea trend. These values indicate a classification right in the middle of the window for this magma to be considered sub-alkaline tholeiitic basalt. Plots of MgO concentration versus pressure and depth for the magmas of Mauna Kea (Figures 10 & 11) show consistent MgO values, regardless of pressure or depth. The majority of the magma chamber pressure and depth values are concentrated at less than 7 km, which doesn't provide a huge variation between the different pressures and depths in order to affect the concentration of these magmas. This consistency also implies that the magma is relatively undisturbed from other processes due to the lack of variation of MgO content.



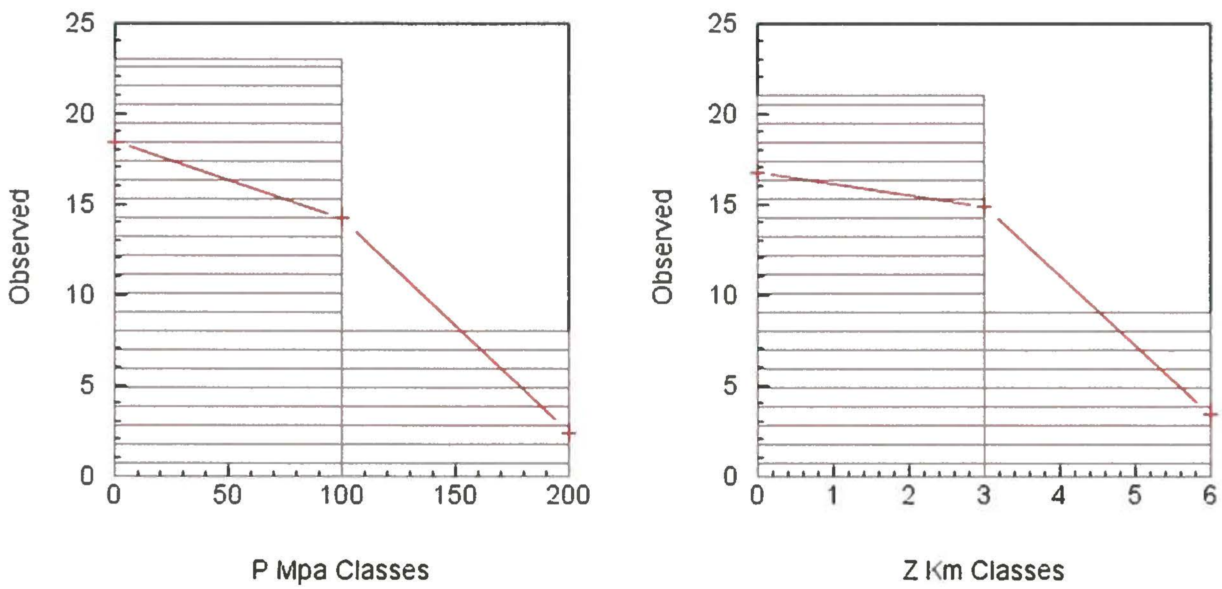


Figures 10 & 11: MgO concentration versus both P MPa and Z Km for Mauna Kea.

Mauna Loa

Mauna Loa is the other large shield volcano considered by this research. The volcano follows the Loa trend, which is consistent with progression from Loihi to the north-west (Dixon & Clague, 2001).

For Mauna Loa, the distribution of magma chambers for both pressure and depth classes versus observed and expected values (Figures 12 & 13) indicate very shallow chambers, located at less than 6 km. The calculated pressure values indicate the same depth for the majority of the magma chambers, despite the fact the plumbing for these magmas may reside at a deeper depth. The pattern these values represent is a graph which shows a steady decrease in the number of measurements as pressure and depth increase.



Figures 12 & 13: The grey histogram blocks represent pressure or depth classes versus observed values, while the red line represents pressure or depth classes versus expected values.

Others have estimated that the Moho is approximately at 18 km beneath Mauna Loa (Putirka, 1997). The distribution of calculated pressures for Loa magmas implies that most crystallize near the surface, at less than 7 km and that the number of magma chambers decreases with depth. This implies a plumbing system that is either present within 7 km or does not have many avenues of transport between the Moho and the surface.

The Mauna Loa magmas plot right in the middle of the bounds of sub-alkaline tholeiitic basalt (Figure 14) an observation consistent with the Loa trend (Dixon & Clague, 2001). The pressure and depth calculations illustrate a consistent classification value for the Mauna Loa volcanics. The percent of silica shows a very narrow range while the alkali component varies. The alkali content is, however, much lower than the values for Loihi, indicating that Mauna Loa has moved off the alkaline-rich portion of the hotspot under the Pacific Plate (Dixon and Clague, 2001).

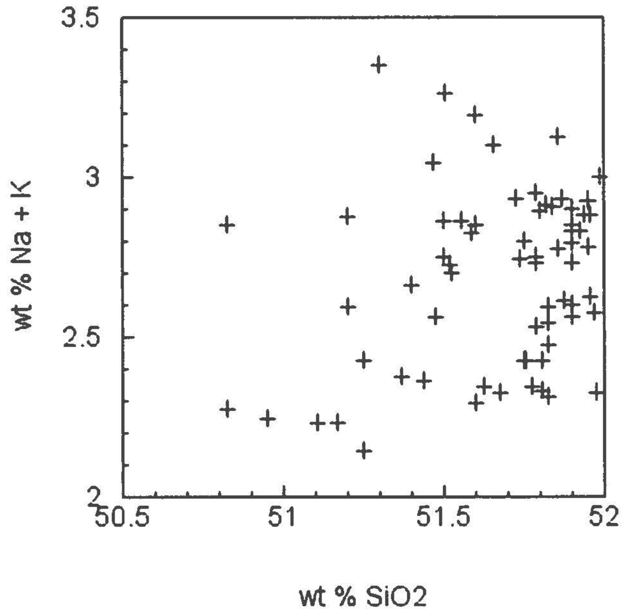
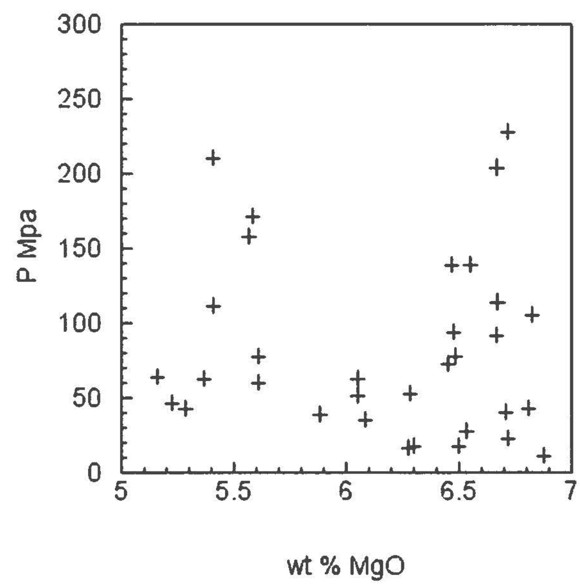
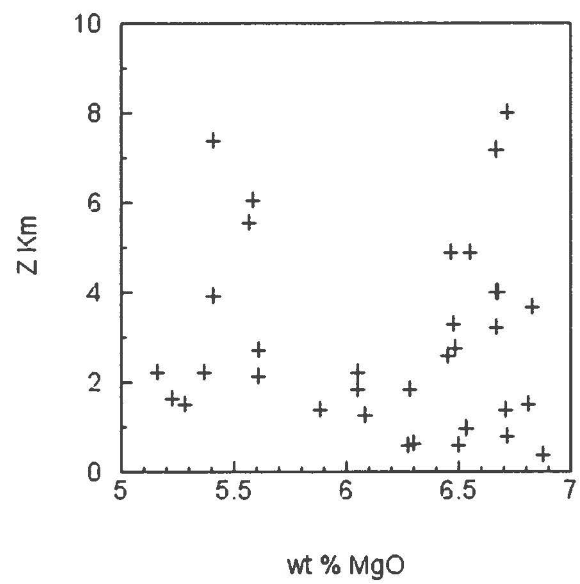


Figure 14: Showing silica versus alkaline ratio for Mauna Loa magmas.





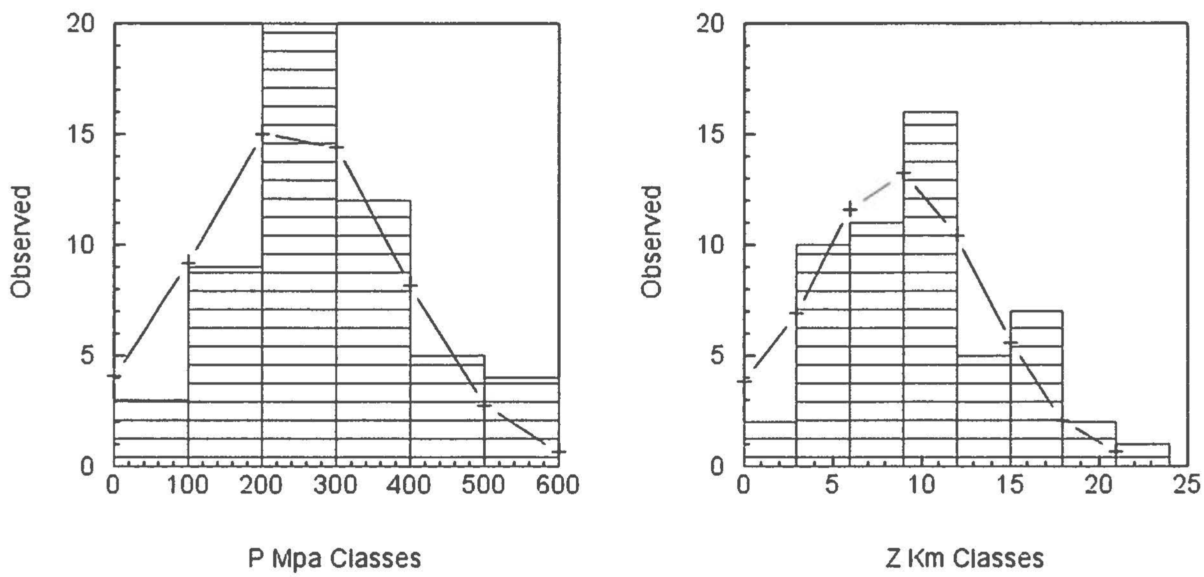
Figures 15 & 16: MgO concentration versus both P MPa and Z Km for Mauna Loa.

Concentration of MgO versus pressure and depth for Mauna Loa indicates a negative slope, which indicates that MgO concentration increases as pressure and depth decrease (Figures

15 & 16). This shows that the magmas must vary in composition with different pressures and depths.

Loihi

Little information exists for Loihi. The volcano is still submerged off the southern coast of the Big Island of Hawai'i by approximately 1,000 meters, so it has not been studied a great deal. It is also the most recent volcano produced by the Hawaiian hotspot (Garcia et al, 2005). The volcano, therefore, is the youngest volcano in the Hawaiian Island chain and certain questions about its composition, magma plumbing, and depth of the magma chambers are very important to help understand the evolution of volcanics in the Hawaiian Islands and about the processes that operate in the intra-crustal magma chambers.



Figures 17 & 18: The grey histogram blocks represent pressure or depth classes versus observed values, while the red line represents pressure or depth classes versus expected values.

Pressure and depth values versus observed and expected data (Figures 17 & 18) provide a very good estimation of how the magma chambers are distributed throughout the crust. For Loihi, the magma chambers are mostly present at around 10 km of depth, with a normal-like distribution on either side. The pressure values have the same pattern with the values centered at around 250 MPa.

These results are consistent with data that suggest alkaline magmas were stored temporarily at relatively shallow depths (< 10 km) but that the magma ascended from a greater depth, and either moved towards the surface or solidified (Garcia et al, 2005). This provides some insight into the magma plumbing systems below the volcano of Loihi. The data agree with the pressure and depths calculated in this research, making the values seem valid and plausible.

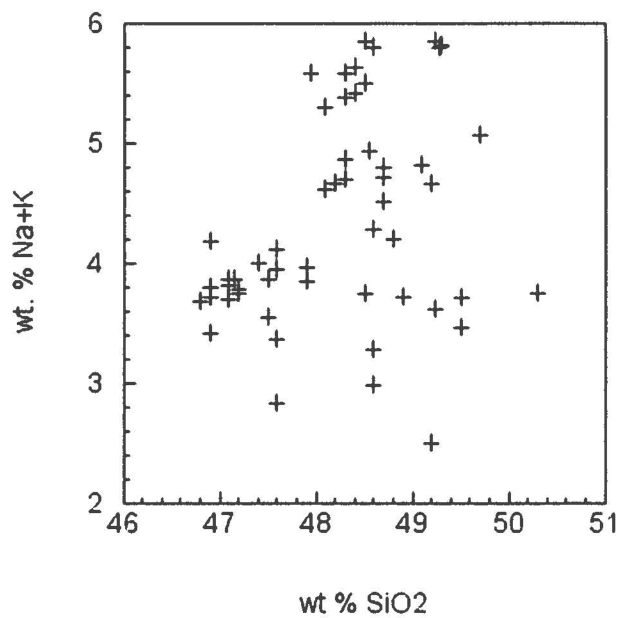
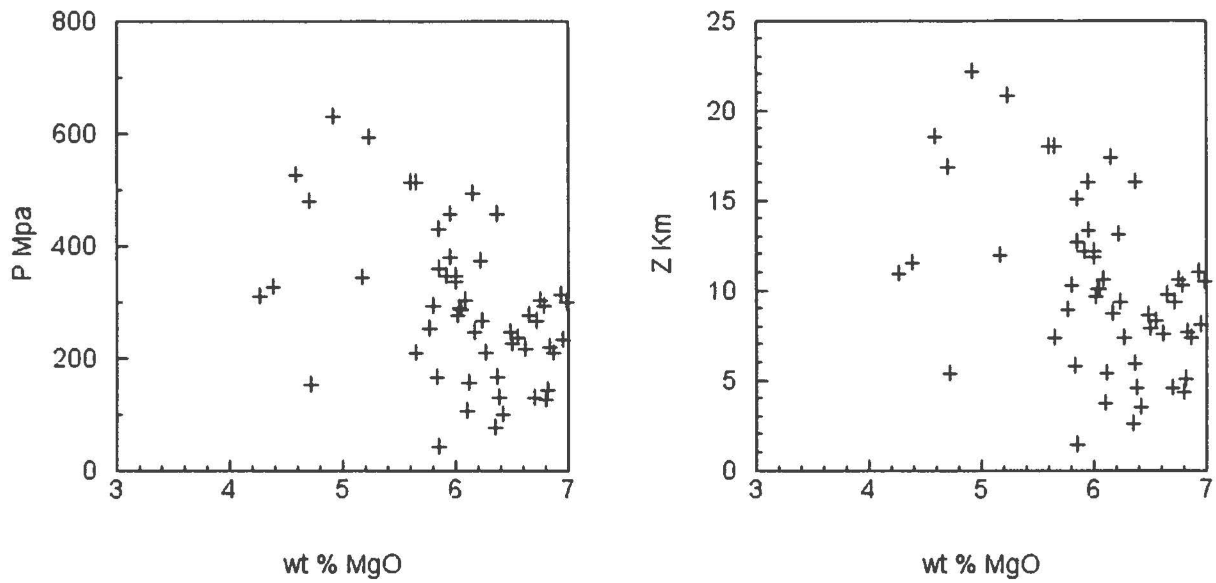


Figure 19: Showing silica versus alkaline ratio for Loihi magmas.

The classification of Loihi magmas indicates that they are more alkaline and contain less silica than the other Hawaiian volcanoes on the Big Island. These magmas are still Basalts, by definition, but they are mostly transitional sub-alkaline magmas or mildly alkaline basalts. This supports the conclusion that Loihi is the most recent Hawaiian volcano as a result of the hotspot and is still in the phase of alkaline-rich magmas that is characteristic of a volcano present on one side of the hotspot (Garcia et al, 2005).

Loihi is a part of the Loa trend, in terms of Hawaiian volcanic progression (Dixon & Clague, 2001). This means that the Mauna Loa volcanics are a natural progression from the Loihi volcanics as the Pacific Plate continues to move over the hotspot and the compositions of these magmas change in each volcano. The Loa trend indicates that Loihi will eventually develop magma of composition similar to that of Mauna Loa.



Figures 20 & 21: MgO concentration versus both P MPa and Z Km for Loihi.

Graphs of pressure and depth vs. MgO content show a negative slope indicating an increase in MgO concentration with decrease of pressure and depth. This means the magma plumbing system beneath Loihi changes in concentration with pressure and depth, and indicates that the mineralogy might be different at these different pressures and depths. This is further substantiated by evidence that Loihi does not have correlation between assimilation and crystal fractionation, implying that the magmatic system at Loihi has not reached a steady state. This result is due to new magmas breaking new ground and being affected by conditions in the crust (Dixon & Clague, 2001).

Discussion

The use of petrological and geophysical methods have allowed many scientists and researchers to use several different methods in order to come to a conclusion on the answers to the same questions that everyone is asking. This is that the magma chambers in these Hawaiian volcanoes are mostly concentrated within 10 km of the surface, with each volcano having a more specific concentration within those bounds as the results varied from volcano to volcano. The values for pressure and depth that were determined were substantiated by both petrological and geophysical methods, allowing the data to be valid and reliable in determining the depth of these magma chambers.

Suggestions for Future Research

A way to improve on this research would be to increase the amount of samples taken in order to produce a more accurate and reliable set of data to determine magma chamber depths. In addition, this would allow the plumbing systems of the entire volcanic systems on the big island of Hawai'i to eventually be determined, through Petrological, Geochemical, and Geophysical methods. Time will eventually allow additional methods to be used and that will provide more accurate results. And more money to fund different methods of research will allow a lot more testing to be done on these systems to help determine how these volcanic processes work in the Hawaiian Island chain.

References Cited

Davis, M.G., Garcia, M.O., and Wallace P. 2003. Volatiles in glasses from Mauna Loa Volcano, Hawaii: implications for magma degassing and contamination, and growth of Hawaiian volcanoes. Contrib. Mineral Petrol. Vol. 144: 570-591.

Ditkof, J. 2010. Pressures of Crystallization and Depth of Magma Chambers beneath Hawaiian Volcanoes. Unpublished B.S. thesis, The Ohio State University, Columbus, Ohio.

Dixon, J.E., and Clague, D.A. 2001. Volatiles in Basaltic Glasses from Loihi Seamount, Hawaii: Evidence for a Relatively Dry Plume Component. Journal of Petrology, vol. 42: 627-654.

Garcia, M.O., Foss, D.J.P., West, H.B., and Mahoney, J.J. 1995. Geochemical and Isotopic Evolution of Loihi Volcano, Hawaii. Journal of Petrology, vol. 36: 1647-1671.

Helz, R.T. and Wright, T.L. 1992. Differentiation and Magma Mixing on Kilauea's East Rift Zone. Bulletin of Volcanology, 54: 361-384.

Helz, R.T. and Wright, T.L. 1996. Differentiation and Magma Mixing on Kilauea's East Rift Zone: A further look at the eruptions of 1955 and 1960. Part II. The 1960 lavas. Bulletin of Volcanology, 57: 602-630.

Kauahikaua, J., Hildenbrand, T., and Webring, M. 2000. Deep magmatic structures of Hawaiian volcanoes, imaged by three-dimensional gravity models. Geology, Vol. 28: 883-866.

Kelley, D.F., and Barton, M. 2008. Pressures of Crystallization of Icelandic Magmas. Journal of Petrology, Vol. 49: 465-492.

Putirka, K. 1997. Magma Transport at Hawaii: Inferences based on igneous thermobarometry. Geology. Vol. 25: 69-72.

Ryan, M.P. 1988. The Mechanics and Three-Dimensional Internal Structure of Active Magmatic Systems: Kilauea Volcano, Hawaii. Journal of Geophysical Research, Vol. 93, 4213-4248.

Sherrod, D.R., Sinton, J.M., Watkins, S.E., and Brunt, K.M. 2007. Geologic Map of the State of Hawai`i: U.S. Geological Survey Open-File Report 2007-1089, 83 p., 8 plates, scales 1:100,000 and 1:250,000, with GIS database.

Yang, H.J., Frey, F.A., Clague, D.A., and Garcia, M.O. 1999. Mineral chemistry of submarine lavas from Hilo Ridge, Hawaii: implications for magmatic processes within Hawaiian rift zones. Contrib. Mineral Petrol. 135: 355-372.

Yang H.J., Frey, F.A., Clague, D.A., and Garcia, M.O. 1994. Submarine lavas from Mauna Kea Volcano, Hawaii: Implications for Hawaiian shield stage processes. Journal of Geophysical Research, vol. 99: 15,577-15,594.